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A Ti-Fe-Sn thin film assembly for joining tungsten and reduced activation ferritic-martensitic steels

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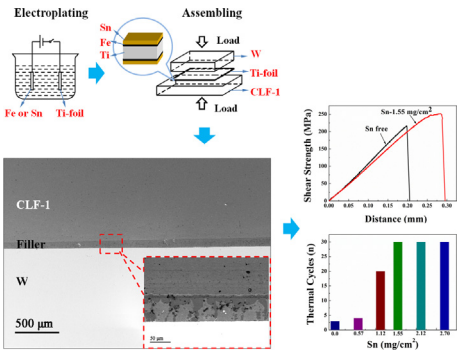
HIGHLIGHTS

- A Ti-Fe-Sn thin film assembly was designed for brazing W and reduced activation ferritic/martensitic steels.
- W/steel joints free of pores and cracks were obtained by vacuum brazing at 1090 °C.
- The W/steel joints demonstrated high strength and high thermocycling stability.
- The presence of Sn in the brazed joints depressed the formation of defects and resulted in microstructure refinement.

GRAPHICAL ABSTRACT



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ABSTRACT

The effective joining of tungsten and reduced activation ferritic-martensitic (RAFM) steels is crucial to fabrication of the divertor components of fusion reactors. In the present work, a low neutron-activation filler metal system of Ti-Fe-Sn was designed to realize the so-called exothermic-reaction-assisted brazing. A series of three-layered Ti-Fe-Sn thin film assemblies were made by electroplating, which allowed the brazing of tungsten with a CLF-1 RAFM steel to be carried out at a temperature as low as 1090 °C. The joint structures made from the Sn-bearing filler metals demonstrated high strength and high resistance against thermocycling. The Sn-film layer in the filler assembly has delivered favorable alloying effects on depressing separation of Ti element in the W grain boundaries and the formation of pores, and on microstructure refinement in the brazed joints as well.

1. Introduction

In the current design of helium-cooling divertors for fusion DEMO reactors, tungsten (W) and its alloys are considered as the plasma-facing component due to their excellent thermo-physical properties such as high melting point, high sputtering resistance, high thermal conductivity and low thermal expansion [1,2]. In the divertor structures, small W tiles (~5 mm thick) are brazed to a thimble structure made of W-alloys to form a cooling finger unit, and such a cooling unit is jointed to a supporting structure made of reduced activation ferritic-martensitic (RAFM) steels [3,4]. The goal of the structure and material design is to remove a heat load as high as 10 MW/m^2. Moreover, the divertor is required to sustain 100–1000 thermal cycles between the

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operating temperatures (600–700 °C) and room temperature [5]. Strong W/RAFM steel joints are necessarily needed to maintain the structural integrity and stability of divertors during operation.

Conventional fusion and pressure welding are not suitable for joining W and RAFM steels because of the significant differences in their melting points and coefficients of thermal expansion (CTEs) [6]. Brazing and solid-state diffusion bonding (SSDB) have demonstrated some advantages to achieve a strong W/RAFM steel joint [1]. Chehtov et al. [7] obtained crack-free joints between W-1% La_2O_3 and EUROFER 97 RAFM steel by vacuum brazing at 1150 °C with two commercially available Ni-based amorphous ribbon alloys (STE-MET 1039 and BrazeTec 1135). Kalin et al. [8] brazed monocrystalline and powder metallurgy W with a RAFM steel, respectively, at 1150 °C by using a rapidly solidified foil-type filler metal (Ni_{bal}-15Cr-4Mo-4Fe(0.5–1.0)V-7.5Si-1.5B, wt%) and a 0.5 mm thick spacer alloy (50Fe-50Ni) for relaxation of the residual thermal stress in the brazed joint. High stability against thermocycling was reached in the monocrystalline W/RAFM steel joint, while branched cracks were observed in the powder metallurgy W substrate. On the other hand, the use of a nickel alloy is not appropriate since Ni element can promote helium accumulation under neutron irradiation, which causes embrittlement of the brazed joint [9–11]. A new filler metal, namely, Fe_{bal}-Ta-Ge-Si-B-Pd, has been further developed by Kalin et al. for brazing W and RAFM steel [10]. Oono et al. [12] reported the effective joining of powder metallurgy W and RAFM steel with Fe-based Fe-*Si*-B amorphous alloys as the filler materials. Although these Fe-based filler metals consist of only low neutron-activation elements, brazing has to be carried out at temperatures (≥1150 °C) higher than the onset temperature of grain growth (1050 °C) in RAFM steels [13,14]. SSDB for joining W and RAFM steel can be conducted at a relatively low temperature. This approach, however, is not suitable for massive production [13]. In addition, the interlayer materials which are used in the SSDB approaches usually contain high activation elements (e.g., Ni [13], Nb [15], V/Ni [16] and V/Cu [17]). Pure titanium [15], Ti-Fe and Ti-Cr-Fe alloys [1], and Ti-Fe powders mixed with an organic binder [18] have also been used to join *W*/W and W/RAFM steel. The common disadvantage of these low activation filler metals is that the formation of defects such as cracks, pores and partial dissolution of W grain boundary, is hardly avoided in the joints [1]. For these reasons, new filler metals are worth developing to fulfill the requirements that are highly demanding by the heterogeneous joints.

In the present work, a low-neutron-activation filler metal system of Ti-Fe-Sn is designed for joining powder metallurgy W and RAFM steels. Considering the enthalpy of mixing and eutectic phase diagram characteristics between the constituent elements, a three-layer structured filler metal assembly has been designed to reach the so-called exothermic-reaction-assisted brazing. In the following, the procedures of filler metal design are first introduced, from which the key parameter of brazing temperature is determined. Brazing experiment is carried out in vacuum using the Ti-Fe-Sn filler assemblies. Examination of the microstructures and mechanical testing indicate that strong W/RAFM steel joints with high thermocycling stability have been successfully obtained.

2. Filler metal design

Ti-Fe and Ti-Sn exhibit strongly negative heats of mixing, $\Delta H_{\text{Ti-Fe}} = -17$ kJ/mol and $\Delta H_{\text{Ti-Sn}} = -21$ kJ/mol [19], indicative of their strong chemical affinity upon alloying. Moreover, the binary Fe-Ti system has a low lying equilibrium eutectic reaction ($L_{\text{Ti70.5Fe29.5}} \leftrightarrow \beta$-Ti + TiFe) at 1085 °C [20]. In view of these thermodynamic characteristics, interface reaction may occur at about 1085 °C in a thin film layered assembly of Ti, Fe and Sn metals. Aktaa et al. suggested that electrodeposition could be used to prepare brazing layers for joining divertor components [4]. In the present fabrication, however, the direct deposition of Sn on the surface of Ti metals is hard to realize in acidic or alkaline electrolytes [21,22]. A very thin layer (<5 μm) of Fe as a transition layer is employed to improve their interface adhesion. Acidic baths are adopted to offer fast deposition rates [21,23]. The electrodeposition procedures are optimized by adjusting the current density and the pH value of the acidic baths so that the assembly surface is free of cracking and peeling. The thickness of the Sn layer in the assemblies is tuned by controlling the current density and/or deposition time.

When heated to a temperature close to 1085 °C, the exothermic interface reaction of Ti foil with RAFM steel and Fe-plating film may take place, and the drastic heat release would cause the melting of the layered film structure. The previous studies have already shown that, when brazing W and RAFM steels with Ti and Ti-Fe filler metals, Ti atoms always diffuse into W grain boundaries and lead to the partial dissolution of W substrate [1]. Noticing the low melting temperature of Sn (232 °C), alloying of Ti with Sn will take place while heating to and holding at the brazing temperature, since Sn has a considerable solid solution limit in a Ti host and a number of intermetallic compounds can form at Ti-rich Ti-Sn compositions [20]. Hence, the Sn-plating film would trap a certain amount of Ti atoms in the bonding seam through formation of Ti-based solid solution and/or intermetallic phases. A Sn film with favorable thickness in this assembly therefore would behave as a blocking layer to depress grain boundary dissolution in the W substrate.

Ti, Fe and Sn atoms have greatly different Goldschmidt radii ($R_{\text{Ti}} = 0.146$ nm, $R_{\text{Fe}} = 0.127$ nm and $R_{\text{Sn}} = 0.155$ nm) [24]. The atomic size complexity frustrates the tendency of their alloy melts to crystallize [25]. A certain level of liquid undercooling may be reached before solidification. The sluggish interatomic diffusion kinetics in the undercooled liquid favors a high crystal nucleation rate but a low growth rate. Consequently, in the solidification process fine-grained microstructures may form in the brazed joints. The validity of this filler metal design has been confirmed in our brazing and mechanical testing experiments.

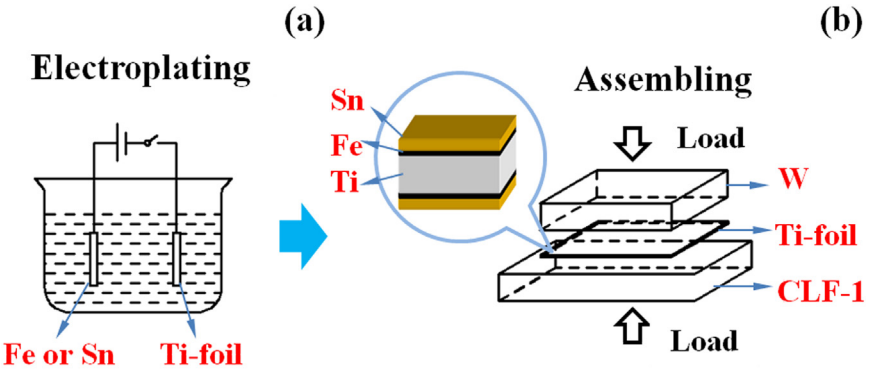

Fig. 1. Schematic illustration of (a) the fabrication of Ti-Fe-Sn thin film assembly by electroplating and (b) the sample assembly prior to brazing.